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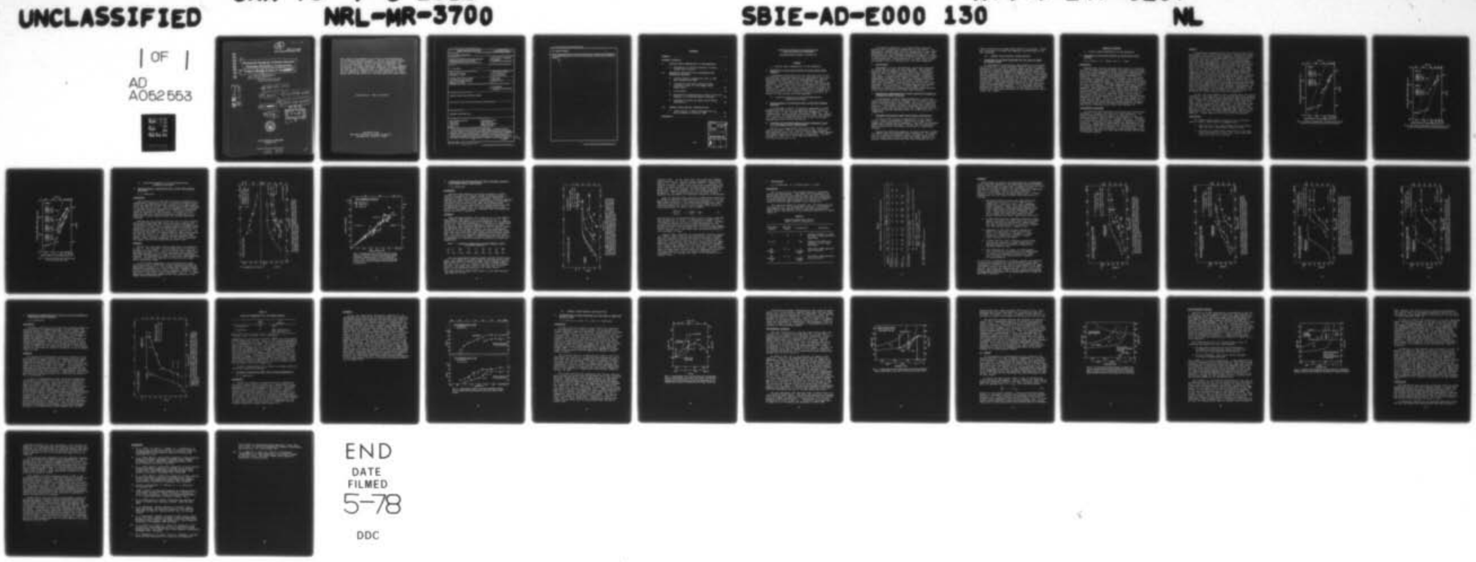

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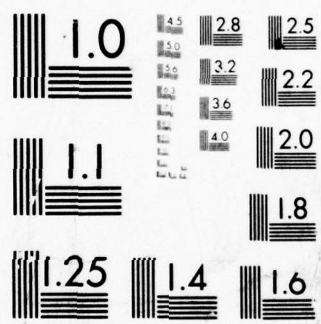

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NRL Memorandum Report 3700

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Structural Integrity of Water Reactor Pressure Boundary Components

9 Progress Rep[redacted]t Ending 31 Aug[redacted]77

10 Frank [redacted] J Loss Editor

Thermostructural Materials Branch
Engineering Materials Division

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12 43p.

NAVAL RESEARCH LABORATORY
Washington, D.C.

251 950

Distribution: NRC-1 and NRC-5

Available from
National Technical Information Service
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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
NRL Memorandum Report 3700

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
STRUCTURAL INTEGRITY OF WATER REACTOR PRESSURE BOUNDARY COMPONENTS PROGRESS REPORT ENDING 31 AUGUST 1977

5. TYPE OF REPORT & PERIOD COVERED
Interim report on a continuing NRL problem.

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
F. J. Loss, Editor   see site supplied data

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Research Laboratory
Washington, D. C. 20375

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
NRL Problem M01-40
Project AT(49-24)-0207

11. CONTROLLING OFFICE NAME AND ADDRESS
U.S. Nuclear Regulatory Commission
Division of Reactor Safety Research
Washington, D.C. 20555

12. REPORT DATE
January 1978

13. NUMBER OF PAGES
41

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES
Distribution includes NRC-1 and 5.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Nuclear pressure vessel steels	Post-irradiation recovery
Warm prestress	Residual impurities
Thermal shock	Fatigue crack propagation
Charpy-V test	Radiation sensitivity

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes research progress in a continuing program to characterize materials properties performance with respect to structural integrity of light water reactor pressure boundary components. Progress for this reporting period is summarized in the following areas: ~~(a)~~ evaluation of critical factors in crack growth rate studies in a pressurized water reactor environment; ~~(b)~~ irradiation and postirradiation (annealing) heat treatment study of the toughness of pressure vessel steels having a low upper shelf level; ~~(c)~~ exploratory investigation of notch ductility changes in → next page
(Continues)

20. Abstract (Continued)

A508-2 forgings; (d) compositional variables affecting upper shelf toughness; and (e) investigation of warm prestress phenomenon as a means to limit crack extension in a vessel during a loss-of-coolant accident.

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STRUCTURAL INTEGRITY OF WATER REACTOR PRESSURE BOUNDARY COMPONENTS

PROGRESS REPORT ENDING 31 AUGUST 1977

SUMMARY

I. FATIGUE CRACK PROPAGATION IN LWR MATERIALS

A. Evaluation of Critical Factors in Crack Growth Rate Studies

A phenomenon associated with the starting level of ΔK was recently identified wherein the crack growth rate for a given stress intensity factor range appeared to increase inversely with the level of ΔK at which the test was initiated. To investigate this phenomenon, tests were conducted in a water pot with starting ΔK levels of 32 and 49 $MPa\sqrt{m}$. However, these tests did not indicate an effect of starting ΔK, Other tests were conducted to investigate the effects of loading ramp time and hold time in a water pot. For variations of 1 to 5 minutes in these parameters, no effect on crack growth rate was observed.

II. RADIATION SENSITIVITY AND POSTIRRADIATION PROPERTIES RECOVERY

A. Second Charpy-V Irradiation Test of NRC 4TCT Program Weld 62N

A second 288°C (550°F) irradiation assessment of 4TCT program weld 62N has been accomplished using a fluence of 9.9×10^{18} n/cm^2 >1 MeV (fission spectrum assumption). The corresponding calculated spectrum fluence, Φ^{cs}, was 1.2×10^{19} n/cm^2 >1 MeV. The exposure was found to reduce the Charpy-V (C_V) upper shelf energy from 103J (76 ft-lb) to the NRC program goal level of 68J (50 ft-lb).

B. Irradiation and Postirradiation Heat Treatment Study of a Low Upper Shelf, A533-B Weld

Trends in C_V upper shelf level with 288°C (550°F) irradiation and 399°C (750°F) postirradiation heat treatment were explored using a 23 cm (9-in.) thick A533-B weld deposit. The copper content of the weld was 0.35 percent. The pre-irradiation upper shelf level was 94J (69 ft-lb).

Note: Manuscript submitted January 13, 1978.

A 39 percent reduction in C_v upper shelf level was observed for a fluence of 2.4×10^{19} n/cm² >1 MeV (Φ^{cs}). The measurement compares well with the projection of upper shelf degradation for the material given by NRC Guide 1.99. The postirradiation heat treatment produced 100 percent recovery in upper shelf energy but only 57 percent recovery in transition temperature. Postirradiation C_v upper shelf energy and dynamic fracture toughness (K_J) were also compared.

C. IAR Program

Experiment 1 of the IAR Program, containing submerged arc welds V84 and V86, has been completed. The primary objective was to explore C_v notch ductility recovery produced by 343°C and 399°C postirradiation heat treatments (168 hour). Both heat treatments were found to produce a high degree of upper shelf recovery; however, transition temperature recovery by the 343°C heat treatment was less than 30 percent compared to 70 percent recovery by the 399°C heat treatment. Doubling the time of the 343°C heat treatment did not result in increased recovery for either material. From the results, it would appear that the kinetics of transition temperature recovery differ significantly from the kinetics of upper shelf recovery.

D. Exploratory Investigation of Notch Ductility Changes in Irradiated A508-2 Forgings

An exploratory study of postirradiation C_v notch ductility and dynamic fracture toughness (K_J) is reported for an A508-2 forging having a high (>135J, 100 ft-lb) C_v correlation at the drop weight nil-ductility transition (NDT) temperature. The results indicate a potential for significant error in predicting the drop weight NDT temperature shift by irradiation from the measured shift in C_v 68J (50 ft-lb) temperature.

E. Variables Influencing Upper Shelf Energy Degradation

Initial results from an investigation on the role of sulfur, copper and phosphorus impurities in upper shelf trends with irradiation are reported. The study is utilizing A302-B steel plates from split (181 kg, 400 lb) laboratory melts produced with statistical variations in impurities content.

Two plates differing primarily in sulfur content (0.017% vs 0.029%) have been evaluated with irradiation. An indication of a greater irradiation effect on upper shelf level for the lower sulfur content plate was found; however, the greater irradiation effect may also be attributed to the

higher preirradiation upper shelf level of this plate. Plans are being made to isolate the separate contributions of the two variables.

III. THERMAL SHOCK-RELATED INVESTIGATIONS

A. Investigation of Warm Prestress for the Case of Small ΔT During a LOCA

An experimental investigation was conducted to characterize the benefits of warm prestress (WPS) in limiting crack extension in the wall of a nuclear vessel during a LOCA-ECCS. The present research emphasized material behavior under conditions of a small ΔT between the temperature of WPS and the failure temperature as might occur during a LOCA. The results have demonstrated that fracture will not occur during a simultaneous unloading and cooling of the crack-tip region following WPS even though the critical K_{Ic} of the virgin material is achieved. Also demonstrated was the fact that for the conditions investigated, fracture will not occur unless the level of WPS has been exceeded. It is concluded that WPS produces an "effective" elevation in K_{Ic} and that this elevation will limit crack extension in the vessel wall so as to retain the coolant.

RESEARCH PROGRESS

I. FATIGUE CRACK PROPAGATION IN LWR MATERIALS

A. Evaluation of Critical Factors in Crack Growth Rate Studies

H. E. Watson, B. H. Menke, and F. J. Loss

BACKGROUND

Experimental results discussed here relate to an evaluation of the effect of starting ΔK, rise time, and hold time on fatigue crack propagation (FCP) in A508-2 forging material. Tests are being conducted in accordance with a preliminary matrix developed by the Nuclear Regulatory Commission to simulate: (a) the hydro and leak transient, (b) the heatup and cooldown transient, and (c) the steady state operation of a nuclear pressure vessel. The primary objective of these tests is to define the important test variables to be used in the main test program. All data reported here were obtained in a water pot operating at 93°C (200°F) and atmospheric pressure. Test specimens used in these tests are 25mm (1 in.) thick compact tension (CT). The loading wave form was a modified trapezoid with a variable ramp and hold time, and the R-ratio used for all tests was 0.125. Crack length measurements are determined by the compliance method wherein changes in the crack length are computed from changes in the mouth opening (CMO). In all cases, the crack growth rate, da/dN, values are determined by computer analysis using the incremental polynominal technique recommended by the ASTM Task Group on Fatigue Crack Growth Rate Testing (1).

EXPERIMENTAL PROCEDURE

The FCP data were generated using water pot fatigue test equipment to simulate the hydro and leak transients. The water chemistry specification (2) is identical to the pressurized water reactor (PWR) system except for hydrogen; for these tests a cover gas of nitrogen was used. The water is circulated through the test chamber to maintain a uniform chemistry. Crack length measurements are referenced to the CMO and are determined using a linear variable differential transformer (LVDT) which operates in the environment. LVDT measurements are then converted to crack lengths using compliance data obtained from specimens having machined notches of different depths.

RESULTS

A phenomenon, associated with the starting level of ΔK, was recently identified by Westinghouse. Results from FCP experiments from the same steel appeared to exhibit a trend in growth rate that is proportional to the level of ΔK at which the test was initiated. To verify this phenomenon, two tests were conducted at a level of starting ΔK higher than that normally employed. All previous tests were initiated at a ΔK of 32 $MPa\sqrt{m}$ (29 $ksi\sqrt{in.}$) while the new tests had an initial ΔK of 49 $MPa\sqrt{m}$ (45 $ksi\sqrt{in.}$). In the first test, Fig. 1, specimen FW-10 was cycled with a load/unload time of 1 sec and a hold time of 60 sec. These data were compared with data from a previous test (FW-2) conducted under identical conditions except for starting ΔK. A second test having a high initial ΔK (49 $MPa\sqrt{m}$) was conducted for loading and hold times of 1 and 3 minutes, respectively, under the same loading conditions (Fig. 2). Due to the lack of sufficient forging material, an A533-B plate specimen was used for the comparison at a high level of starting ΔK. The data from preceding tests do not indicate a significant effect of starting ΔK in the range from 32 to 49 $MPa\sqrt{m}$. However, an additional test is planned with a starting ΔK of 22 $MPa\sqrt{m}$ to further evaluate this test parameter.

In Ref. 3 it was reported that a loading wave form which combined a 1 min ramp with a 3 min loading hold time produced the highest crack growth rates observed at NRL for this material. These data are repeated along with other reference data in Fig. 3. In addition, data from a 5 min ramp, 1 min hold time are presented for comparison. The data from this test (specimen FW-8) closely match the data from the test with a 1 min ramp, 3 min hold time (specimen FW-14). A comparison of these two specimens suggests that increasing the ramp time from 1 min to 5 min does not affect FCP in this material. Longer ramp and hold time tests are planned.

CONCLUSIONS

For A508-2 forging material and the test conditions used to conduct these tests, it appears that:

1. Starting ΔK in the range between 32 and 49 $MPa\sqrt{m}$ does not have a significant effect on FCP.

2. Changing the loading wave form from a 1 min rise, 3 min hold time to a 5 min rise, 1 min hold time, does not affect the test data.

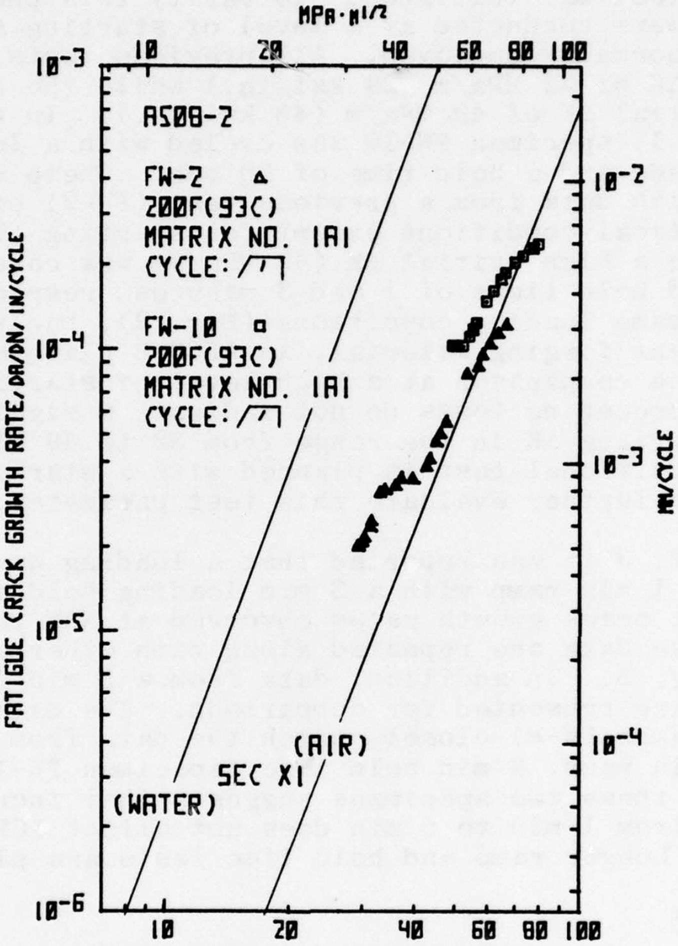

Fig. 1 — The effect of starting ΔK in the range between 32 and 49 MPa$\sqrt{m}$ (Specimens FW-2 and FW-10, respectively)

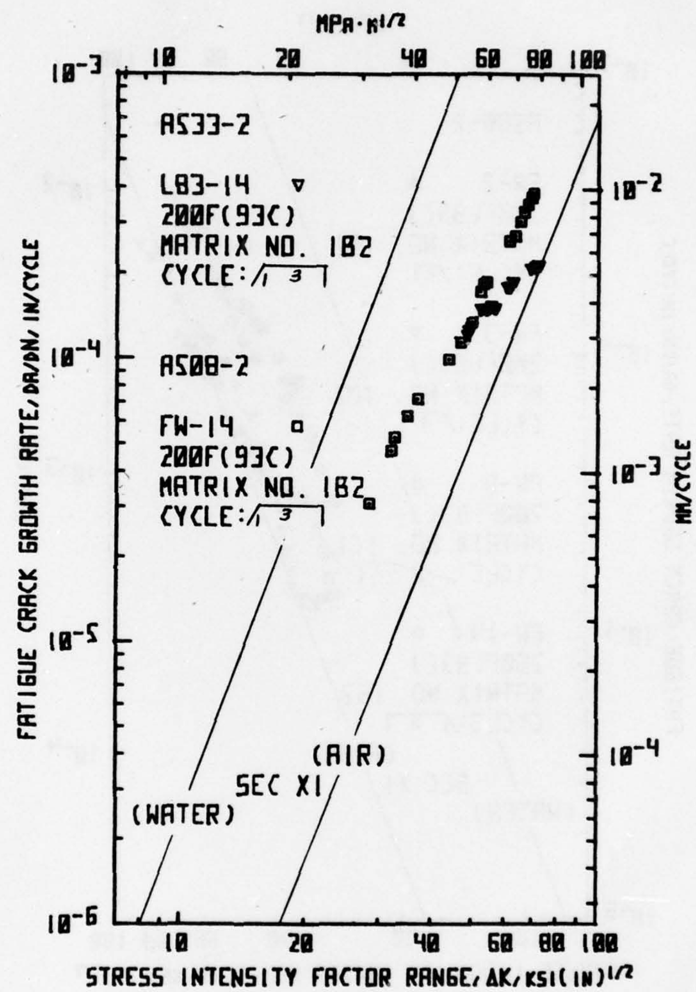

Fig. 2 — The effect of starting ΔK in the range between 32 and 49 MPa$\sqrt{m}$ (Specimens FW-14 and L83-14, respectively)

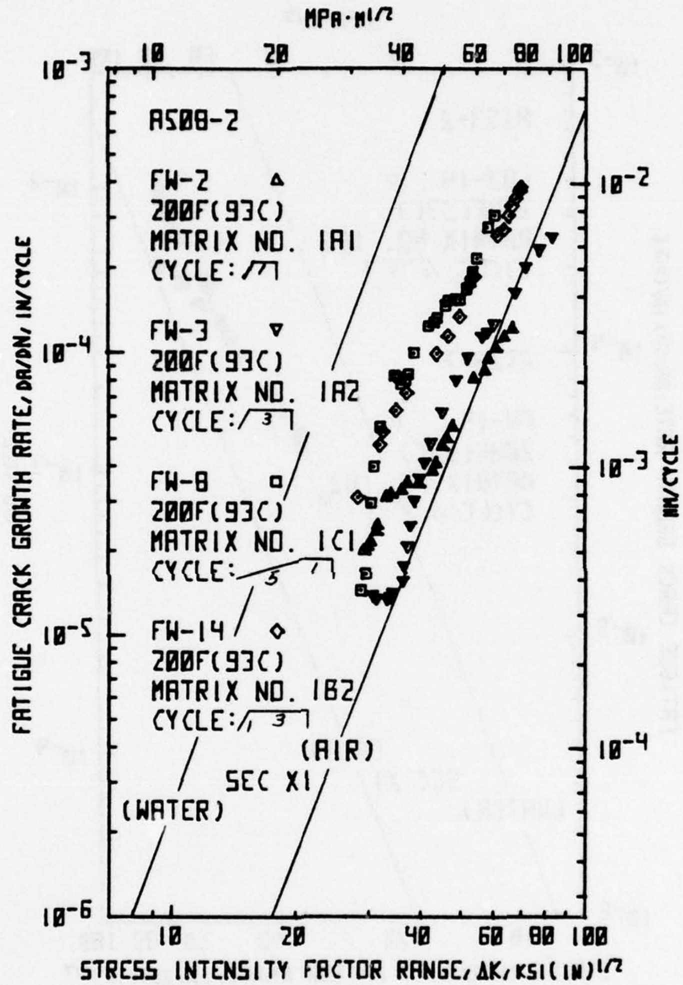

Fig. 3 — Data resulting from tests conducted using a range of loading wave forms

II. RADIATION SENSITIVITY AND POSTIRRADIATION PROPERTIES RECOVERY

A. Second Charpy-V Irradiation Test of NRC 4TCT Program Weld 62N

J. R. Hawthorne

BACKGROUND

One objective of the NRC 4TCT irradiation program is to assess metal toughness in terms of fracture mechanics parameters for materials exhibiting a Charpy-V (C_V) upper shelf level near 68J (50 ft-lb). For 4TCT program welds, knowledge of the particular neutron exposure necessary to reduce pre-irradiation toughness levels to the target postirradiation level is essential to NRC planning. In support of this planning, NRL has conducted preliminary experiments on C_V upper shelf trends versus fluence for the weld materials selected.

Results for the initial radiation test of three program welds (weld Codes 62N, 63N and W) have been reported (4). The fluence level based on a fission spectrum assumption was $\sim 7 \times 10^{18}$ n/cm^2 >1 MeV. The calculated spectrum fluence corresponding to this fluence is 8.5×10^{18} n/cm^2 >1 MeV based on a recent spectrum analysis for the exposure facility (5). In the case of weld 62N, the postirradiation upper shelf energy was 79J (58 ft-lb); i.e., higher than the initial target value of 68J (50 ft-lb). NRC accordingly requested that a second, higher fluence assessment of the weld be performed. The target fluence level selected was 1×10^{19} n/cm^2.

PROGRESS

Results for the higher fluence experiment are presented in Fig. 4. For reference, the findings of the initial experiment are also shown. It will be noted that a portion of specimens included in the latest experiment were taken from the same specimen group as those for the first experiment. Likewise, the specimens of common origin were postirradiation tested at temperatures spanning the transition and upper shelf temperature range.

In the current experiment, the postirradiation upper shelf was found to be 68J (50 ft-lb), thereby achieving the experimental objective. The corresponding specimen lateral expansion measurement was 1.1mm or 44 mils. Somewhat higher scatter was encountered in lateral expansion values in this case than in the lower fluence experiment (Fig. 5). A higher transition temperature elevation was also produced by the higher fluence irradiation.

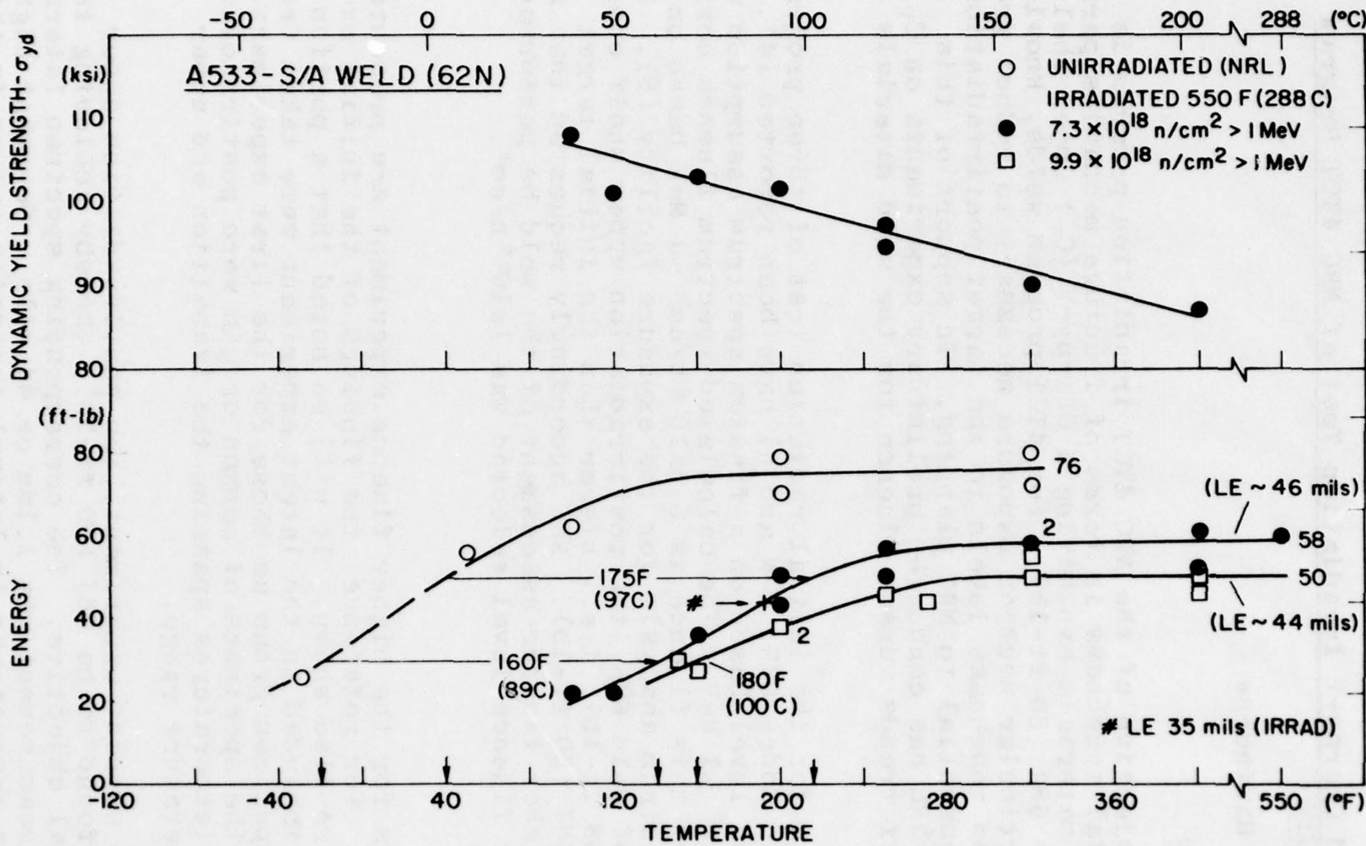

Fig. 4 — Changes in Charpy-V notch ductility observed for Weld 62N for two fluences at 288°C (550°F). Postirradiation dynamic yield strength determinations from Dynatup load vs time traces are also shown for the lower fluence condition (upper graph).

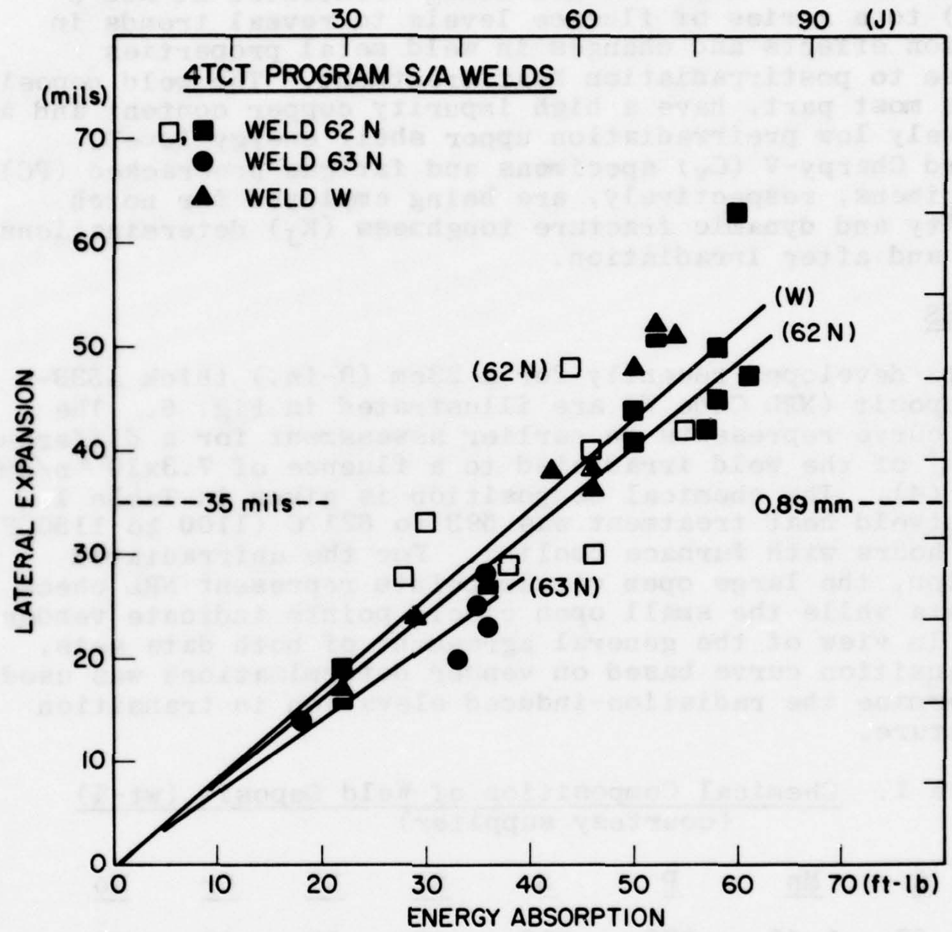

Fig. 5 — Postirradiation Charpy-V lateral expansion vs energy absorption of Weld 62N. The filled and open square symbols, respectively, represent fluences of 7.3×10^{18} and 9.9×10^{18} n/cm^2 > 1 MeV. Lateral expansion vs energy absorption relationships for two other 4TCT program welds, Codes 63N and W, are also shown.

B. Irradiation and Postirradiation Heat Treatment Study of a Low Upper Shelf, A533-B Weld

J. R. Hawthorne

BACKGROUND

Selected weld deposits are being irradiated at 288°C (550°F) to a series of fluence levels to reveal trends in radiation effects and changes in weld metal properties response to postirradiation heat treatment. The weld deposits, for the most part, have a high impurity copper content and a relatively low preirradiation upper shelf energy level. Standard Charpy-V (C_V) specimens and fatigue precracked (PC) C_V specimens, respectively, are being employed for notch ductility and dynamic fracture toughness (K_J) determinations before and after irradiation.

PROGRESS

Data developed recently for a 23cm (9-in.) thick A533-B weld deposit (NRL Code W) are illustrated in Fig. 6. The dashed curve represents an earlier assessment for a different section* of the weld irradiated to a fluence of 7.3×10^{18} n/cm² >1 MeV (4). The chemical composition is given in Table 1. The postweld heat treatment was 593 to 621°C (1100 to 1150°F) for 24 hours with furnace cooling. For the unirradiated condition, the large open circle points represent NRL check test data while the small open circle points indicate vendor data. In view of the general agreement of both data sets, the transition curve based on vendor determinations was used to determine the radiation-induced elevation in transition temperature.

Table 1. Chemical Composition of Weld Deposit (wt-%) (courtesy supplier)

Cu	C	Mn	P	S	Si	Ni	Cr	Mo
.35	.09	1.45	.020	.013	.68	.57	.06	.39

The new experimental results permit several observations. First, the fluence of 2.0×10^{19} n/cm² >1 MeV reduced the weld upper shelf level to below the ASME Code C_V energy index of 68J (50 ft-lb) that is required in order to define RT_{NDT}. Secondly, the upper shelf energy reduction (ΔE) is about equal to that measured earlier at the lower fluence

*The preirradiation upper shelf level of this weld section was 104J (77 ft-lb).

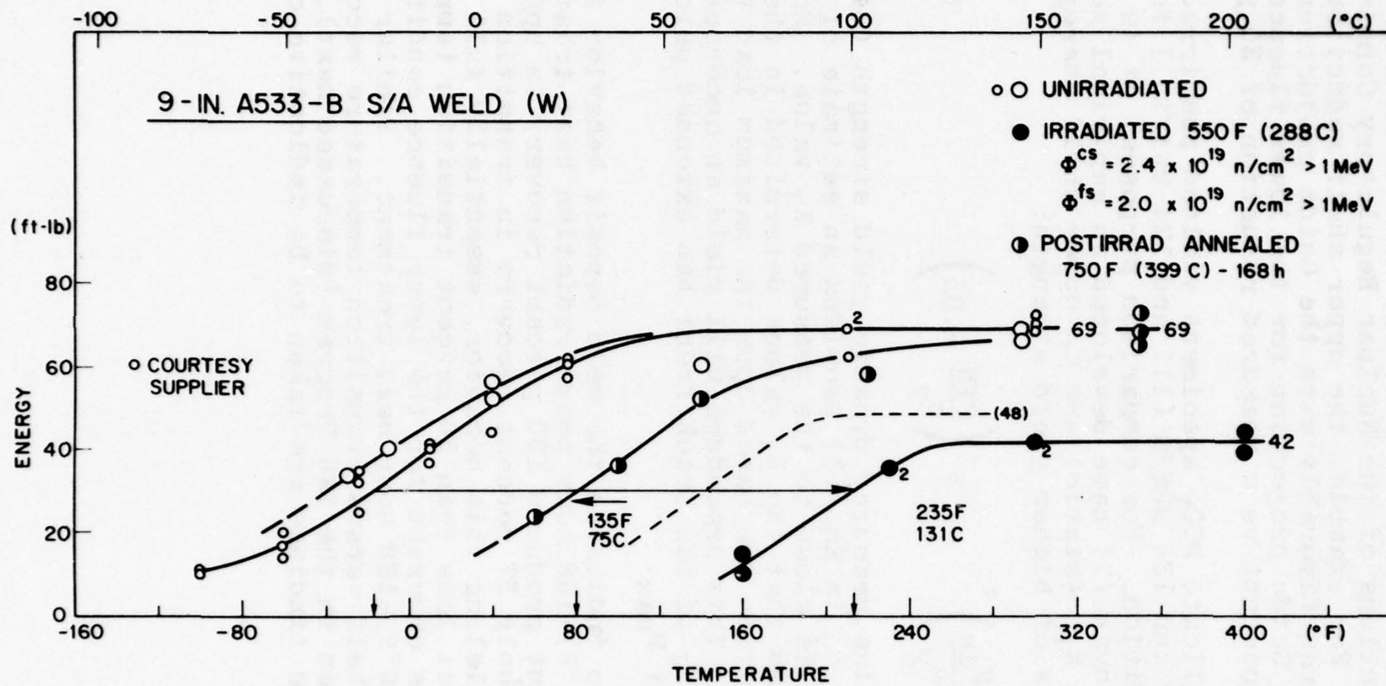

Fig. 6 — Charpy-V notch ductility of the A533-B submerged arc weld deposit after irradiation and after postirradiation heat treatment. Irradiation is seen to reduce the upper shelf energy level below the Code index value of 68J (50 ft-lb) minimum; however, full upper shelf recovery was obtained by heat treating. The dashed curve refers to a 7.3×10^{18} n/cm^2 exposure for a different weld section, having a 104J (77 ft-lb) initial upper shelf.

(dashed curve). On the other hand, the transition temperature elevations for the two fluence exposures differ appreciably, i.e., 131°C (235°F) vs 89°C (160°F). Thirdly, the observed changes in upper shelf energy are conservative with respect to projections of the Nuclear Regulatory Commission Guide 1.99 (6). For example, the upper shelf reduction of 39 percent compares favorably with the Guide projection of 46 percent. The Guide projection for the lower fluence exposure was 40 percent vs a measured reduction of 30 percent.

Tests of duplicate PCC_V specimens yielded postirradiation K_J values of 129 and 136 MPa$\sqrt{m}$ (117 and 124 ksi$\sqrt{in.}$) for the upper shelf condition. For comparison purposes, it is noted that Rolfe and Novak (7) have developed an empirical relationship between K_{Ic} (static) and C_V upper shelf energy for structural steels of higher yield strength:

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 = 5\left(\frac{CVN}{\sigma_y} - .05\right) \tag{1}$$

Substitution of the measured dynamic yield strength (645 MPa) for the weld for σ_y in Eq. (1) provides an estimate of K_J (145 MPa$\sqrt{m}$) that is close to the measured K_J value. However, it should be noted that the K_J values determined in the present investigation are based upon the maximum load (P_{max}) during the test. This procedure will yield an unconservative (high) value of K_J if the crack front has extended prior to the attainment of P_{max}.

Figure 6 also indicates the weld deposit behavior following a 399°C (750°F)-168 hour postirradiation heat treatment. The heat treatment produced 100 percent recovery in upper shelf level but only 57 percent recovery in transition temperature. Paralleling this behavior, essentially full upper shelf recovery but less than 50 percent transition temperature recovery was observed for the lower fluence condition with a 343°C (650°F)-168 hour heat treatment. Similar differences in upper shelf versus transition temperature recovery have been observed in the IAR Program (discussed next). Consequently, the findings are taken to be indicative of a general trend.

C. IAR Program

J. R. Hawthorne, H. E. Watson and F. J. Loss

BACKGROUND

The initials of the IAR Program stand for "Irradiate, Anneal and Reirradiate". The intent of the program is to investigate material performance under two full annealing and reirradiation cycles such that the merits and potential of postirradiation heat treatment as a method to control radiation-induced embrittlement can be identified.

In a previous report of progress (3), the background and the objectives of the program were outlined. The planned experimental test matrix (Table 2) was also discussed together with a description of the materials selected for study (Table 3).

Table 2

Radiation Experiment Matrix
288°C (550°F) Irradiation

Experiment Number	Specimen Types	Designation	*Objective*
1	C_v	IA	Explore recovery by 343 and 399°C (650 and 750°C) annealing
2 A,B,C	C_v	IAR	Explore reirradiation response of all three materials
3A through 3E	CT, C_v	I through IARAR	Determine IARAR performance of Weld 1
4A through 4E	CT, C_v	I through IARAR	Determine IARAR performance of Weld 2

Table 3

CHEMICAL COMPOSITIONS OF IARAR PROGRAM WELDS AND PLATE

MATERIAL	CODE		Weight (%) Cu	C	Mn	Si	P	S	Ni	Mo	V	Cr
S/A Weld 1 (Linde 1092 flux)	V84	(a)	.35	.14	1.56	.14	.013	.011	.62	.53	.002	.03
S/A Weld 2 (Linde 80 flux)	V86	(a)	.35	.08	1.60	.55	.016	.013	.69	.40	.006	-
Plate 1 (A302-B Mod.)	V85	(a)	.22	.22	1.50	.27	.013	.020	.53	.46	-	-
		(b)	.24	.22	1.45	.30	.011	.014	.52	.48	-	-

Heat Treatment		
	V84	Stress relief annealed 593 to 621°C - 50 hr, furnace cooled to 316°C at 6°C/hr, air cooled.
	V86	Stress relief annealed 621°C - 40 hr, furnace cooled to 316°C.
	V85	843 to 899°C - 4 hr, water quenched 663°C - 4 hr, air cooled 621°C - 40 hr, furnace cooled to 316°C

(a) Vendor determination
(b) Lukens Steel Company determination

PROGRESS

Postirradiation testing and data analyses for Experiment 1 have now been completed. The experiment contained welds V84 and V86 and had the objective of exploring notch ductility recovery with 343°C vs 399°C heat treatments (Table 2). In the case of the 343°C anneal, two heat treatment times were also to be evaluated: 168 hours versus 336 hours. Figures 7 to 10 summarize the experimental data. Primary observations for the listed fluence conditions were as follows:

1. The welds exhibited about the same transition temperature elevation (~111°C, 200°F) with irradiation, consistent with their comparable copper contents. Also, these measured transition temperature elevations were somewhat less than those projected by NRC Regulatory Guide 1.99. Upper shelf reductions, however, were not the same with weld V84 (higher initial shelf) showing the larger upper shelf reduction.

2. A 343°C-168 hour heat treatment produced a high degree of recovery in upper shelf for both welds V84 and V86 (62 and 100 percent, respectively) but only limited recovery in transition temperature (29 and 22 percent, respectively).

3. Extension of the time of heat treatment at 343°C from 168 hours to 336 hours did not result in a significant increase in either transition temperature recovery or upper shelf recovery for the welds.

4. A 399°C-168 hour heat treatment produced both 100 percent recovery in upper shelf and ~70 percent recovery in transition temperature for welds V84 and V86.

5. From observation (4) above, it would appear that the kinetics (and possibly the mechanisms) of transition temperature recovery vs upper shelf recovery are significantly different for weld deposits.

On the basis of Experiment 1 findings, target reirradiation fluences for Experiment 2B (IAR with 343°C anneal) were established at 3×10^{18} n/cm^2 and that for Experiment 2C (IAR with 399°C anneal) has been set at 6×10^{18} n/cm^2 >1 MeV (Φ^{fs}). Reactor operations for Experiments 2A, B and C have subsequently been completed. Also, reactor operations required by Experiments 3A through 3C and Experiments 4A through 4C have been completed.

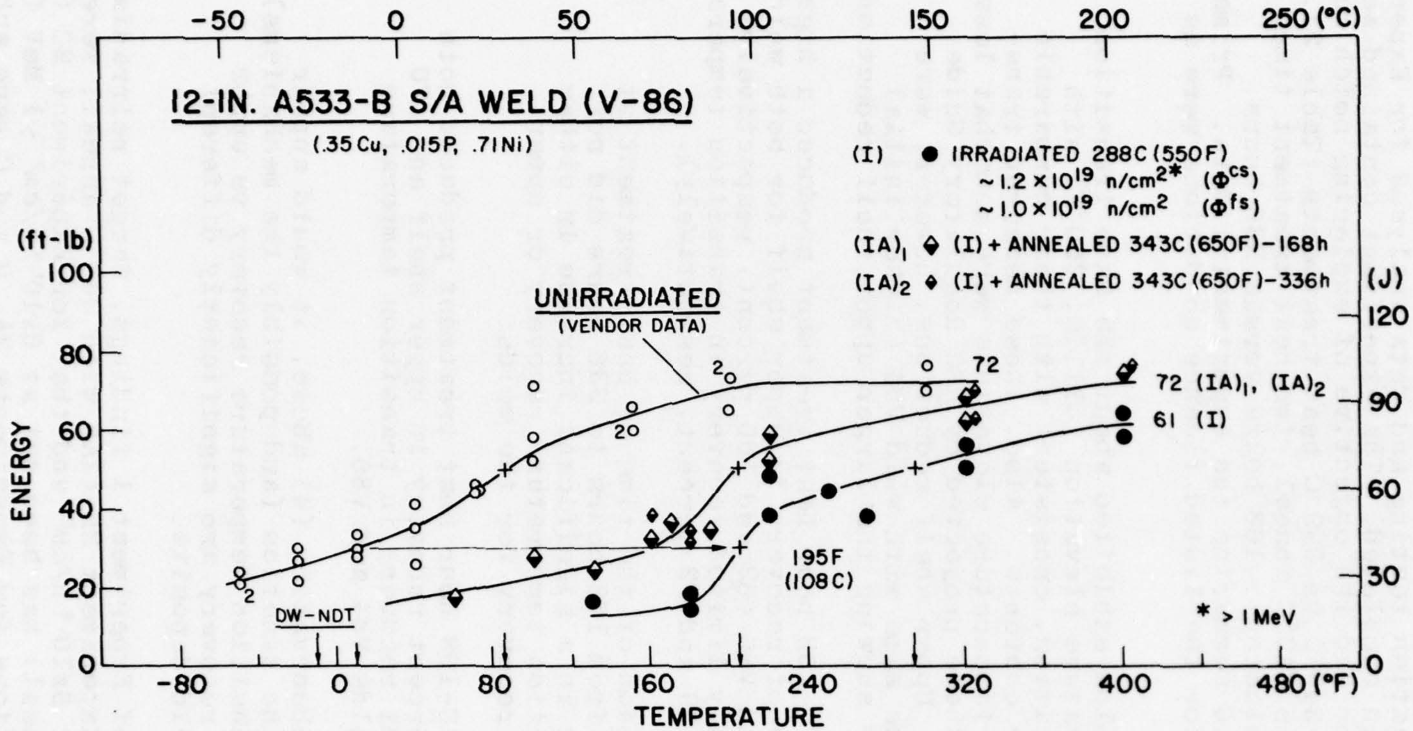

Fig. 7 — Notch ductility of weld V86 by 343°C (650°F) annealing heat treatment for two different times following first cycle irradiation. Full upper shelf recovery but only 22 percent transition temperature recovery (41J, 30 ft-lb index) are observed. No difference in recovery is found between 168 hour and 336 hour heat treatments.

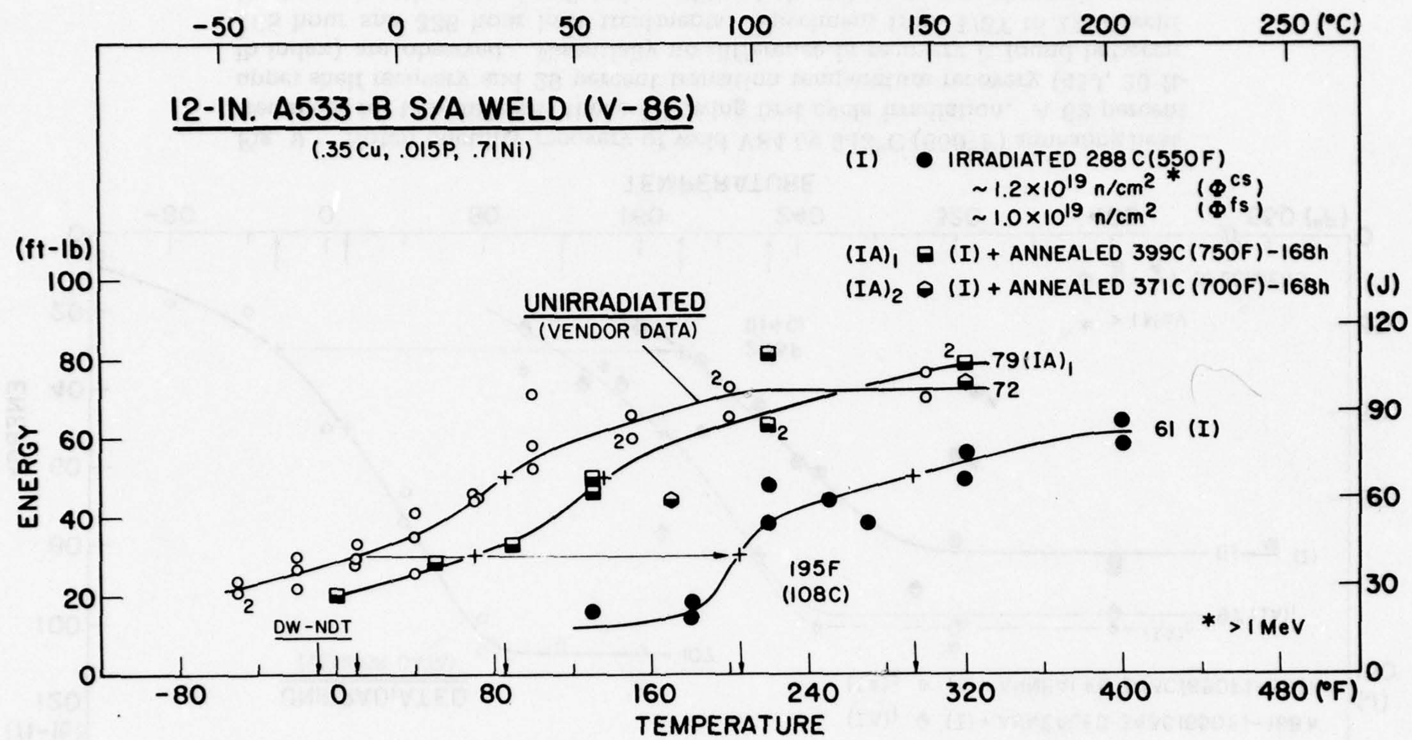

Fig. 8 — Notch ductility recovery of weld V86 by 399°C (750°F) heat treatment following first cycle irradiation. Full upper shelf recovery and 69 percent transition temperature recovery (41J, 30 ft-lb index) are observed. Limited data for the 371°C (700°F) postirradiation heat treated condition are also shown.

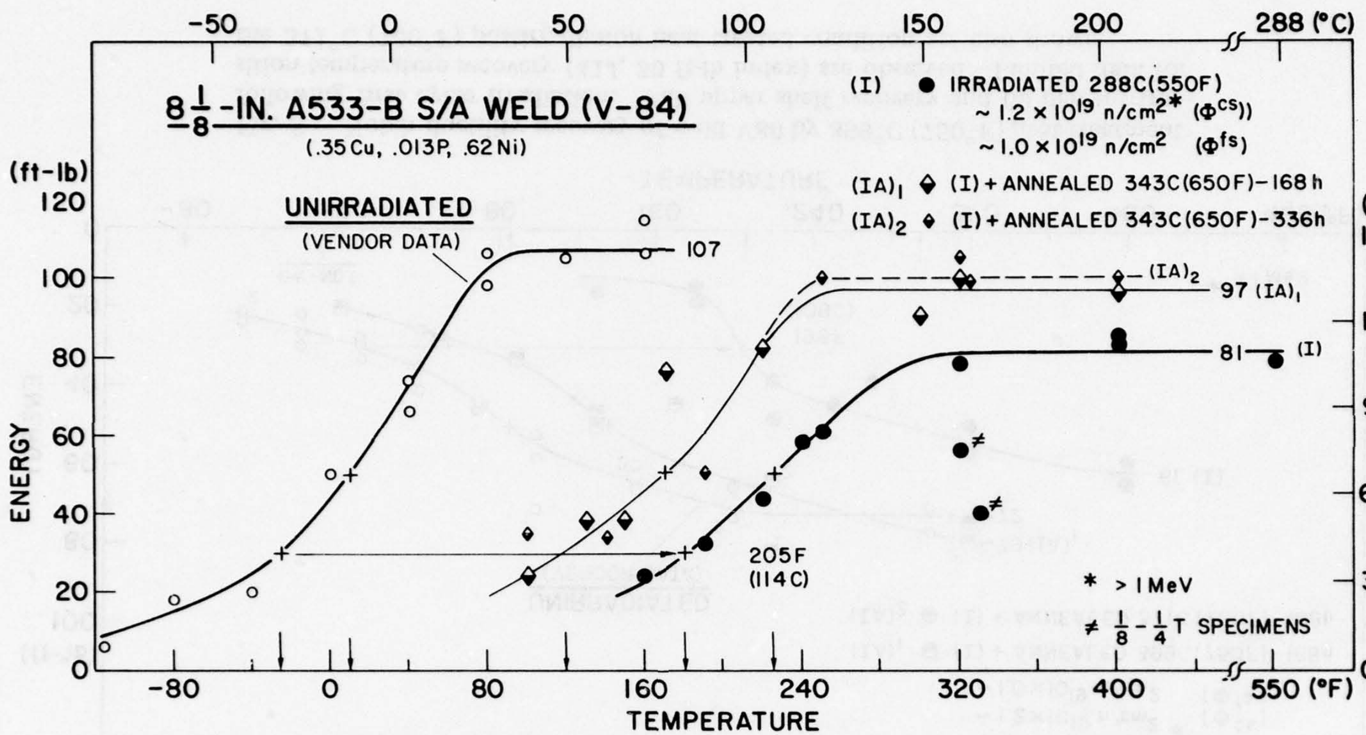

Fig. 9 — Notch ductility recovery of weld V84 by 343°C (650°F) annealing heat treatment for two different times following first cycle irradiation. A 62 percent upper shelf recovery and 29 percent transition temperature recovery (41J, 30 ft-lb index) are observed. Essentially no difference in recovery is found between 168 hour and 336 hour heat treatments. Specimens from 1/8T to 1/4T weld thickness location (see irradiated condition) show low energy absorption compared to the balance of the weld; use of a different weld wire with higher copper content is suspected.

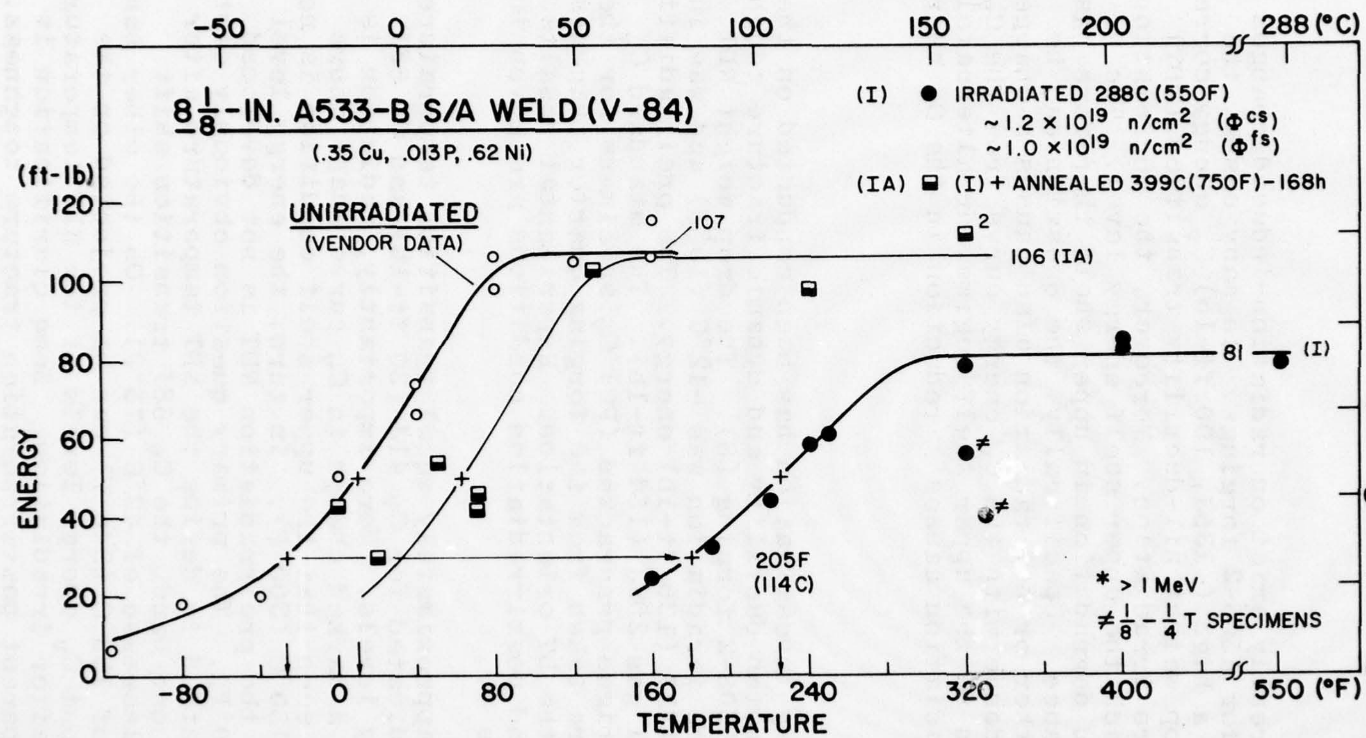

Fig. 10 — Notch ductility recovery of weld V84 by 399°C (750°F) heat treatment following first cycle irradiation. Full upper shelf recovery and 71 percent transition temperature recovery (41J, 30 ft-lb index) are observed.

D. Exploratory Investigation of Notch Ductility Changes in Irradiated A508-2 Forgings

J. R. Hawthorne

BACKGROUND

Few data currently exist on radiation-induced changes to notch ductility for A508-2 forgings. In many cases, the forgings exhibit a high (>135J, 100 ft-lb) C_v energy correlation at the drop weight nil-ductility transition (NDT) temperature before irradiation. Moreover, the correlation energy may approach the upper shelf energy level. The radiation-induced degradation in upper shelf therefore has special significance. Specifically, the question can be raised as to whether or not radiation also causes a change in NDT correspondence with the C_v energy curve from the C_v transition region to the upper shelf regime, or alternately, whether or not radiation causes a reduction in the C_v energy index for NDT.

PROGRESS

An exploratory investigation has been conducted on the postirradiation notch ductility and dynamic fracture toughness (K_J) of an A508-2 forging (8). The drop weight NDT temperature before irradiation was -12°C (10°F) and was indexed by the C_v 183J (135 ft-lb) energy. The preirradiation upper shelf level was 209J (154 ft-lb). The standard C_v specimens and fatigue precracked (PC) C_v specimens for the investigation were taken from the forging quarter thickness location and in the LT orientation. Experimental results for preirradiation and postirradiation conditions are given in Fig. 11 and Table 4.

In Fig. 11, approximately equal transition temperature increases are indicated for C_v 41J (30 ft-lb) and C_v 68J (50 ft-lb) energy levels. More importantly, radiation is shown to produce a marked change in C_v curve shape above 136J (100 ft-lb) such that the upper shelf condition is not attained until ~150°C (300°F). In turn, the energy level corresponding to the preirradiation NDT is not developed until ~121°C (250°F). The primary question obviously centers on the correct method to define the NDT temperature after irradiation. On one hand, the C_v 68J transition shift suggests an NDT increase of 42°C (75°F). On the other hand, an NDT increase of 133°C (240°F) can be projected on the basis of equivalent C_v energy levels at the NDT temperature both before and after irradiation. Some clarification is possible from apparent postirradiation fracture toughness. In Table 4, the observed K_J values suggest that the NDT

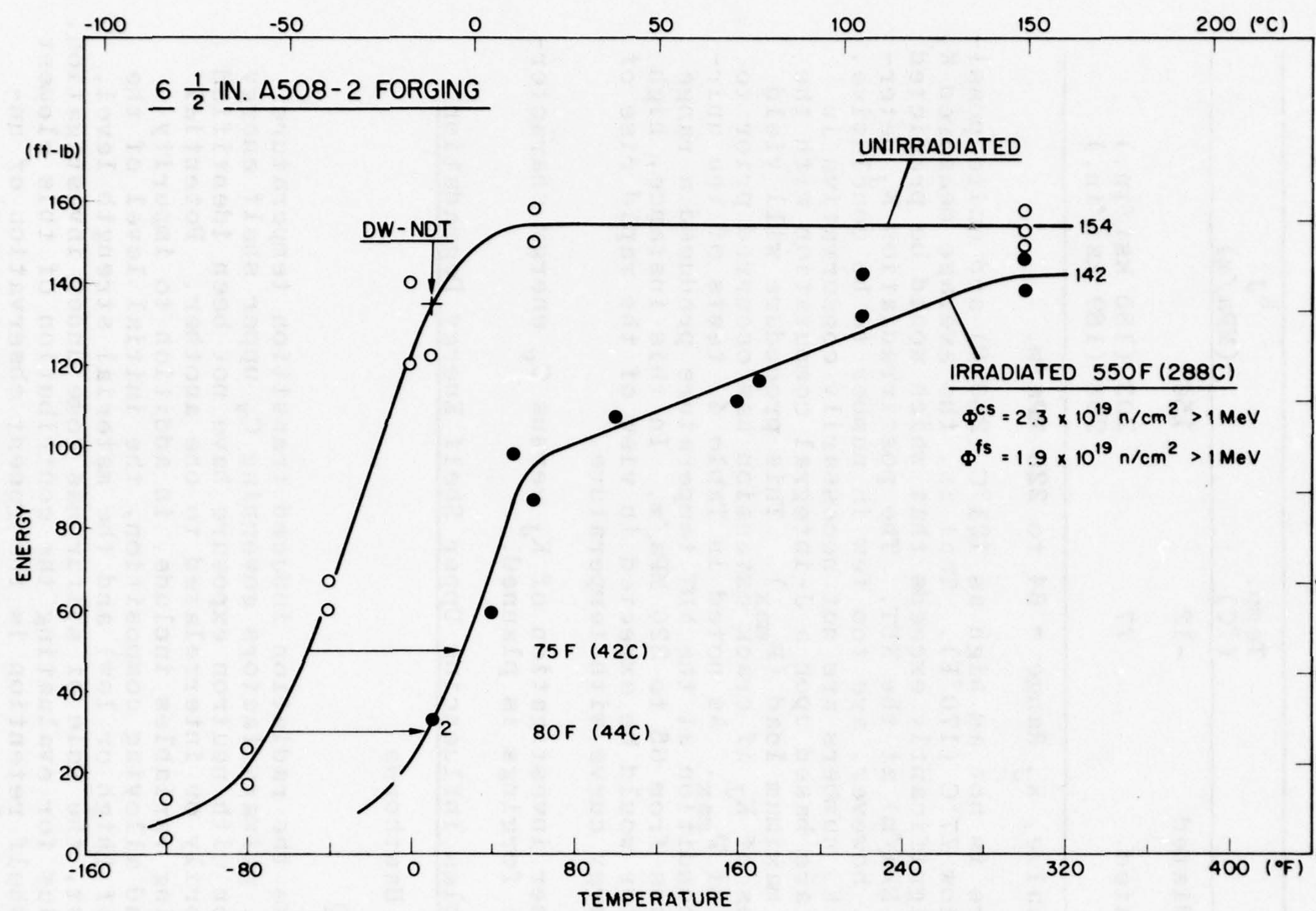

Fig. 11 — Charpy-V notch ductility of the A508-2 forging before and after irradiation. The change in shape of the transition curve with irradiation makes the projected postirradiation NDT temperature based on the Charpy-V 68J (50 ft-lb) transition temperature elevation (conventional method) questionable.

Table 4

Fracture Toughness (K_J) of A508-2 Forging

	Temp. (°C)	K_J (MPa$\sqrt{m}$)
Unirradiated	-12	156[a]
Irradiated	77	203 (185 ksi$\sqrt{in.}$) 208 (189 ksi$\sqrt{in.}$)

[a]Average value, K_J Range = 64 to 220 MPa$\sqrt{m}$.

temperature is not as high as 121°C (250°F) and quite possibly is below 77°C (170°F). That is, the average measured K_J at 77°C significantly exceeds that which would be predicted (60 to 66 MPa$\sqrt{m}$) at the NDT. The postirradiation K_J determinations, however, are too few in number to be conclusive. Also, the K_J numbers are not necessarily conservative in that they are based upon a J-integral computation with the energy to maximum load (P_{max}). This procedure will yield high values of K_J if crack extension has occurred prior to the point of P_{max}. As noted in Table 4, tests of the unirradiated condition at the NDT temperature produced a range of K_J values from 65 to 220 MPa$\sqrt{m}$. In this instance, high data scatter would be expected in view of the rapid rise of the C_v energy curve with temperature.

Further investigation of K_J versus C_v energy characteristics for forgings is planned.

E. Variables Influencing Upper Shelf Energy Degradation

J. R. Hawthorne

BACKGROUND

Unlike the radiation induced transition temperature elevation, primary factors governing C_v upper shelf energy degradation with neutron exposure have not been identified satisfactorily or interrelated to one another. Potential contributing variables include, in addition to impurity element and alloying composition, the initial level of the upper shelf (high or low) and the material strength level. Of interest, the role of sulfur has come under investigation. The stimulus for evaluating the contribution of this element to upper shelf retention is the recent observation of unusually high sulfur concentrations on irradiated fracture surfaces examined by Aüger spectroscopy (4).

PROGRESS

In Fig. 12, upper shelf degradation observed for two irradiated plates differing in sulfur content are shown (8). The A302-B plates were produced for NRL from split (400 lb) laboratory melts which featured statistical variations in copper, phosphorus, and sulfur contents. Simultaneous irradiation procedures were used to effect the comparison; the difference in neutron fluence (small) between the two materials were due to neutron flux gradients over the length of the irradiation assembly. Charpy energy values at 149°C (300°F) were used for postirradiation upper shelf determinations. As noted in Fig. 12, some indication of a greater radiation effect on upper shelf level with a lower sulfur content is given by the data; however, the trend versus increasing sulfur content would be anomalous relative to the Aüger observations. The present observation, on the other hand, is consistent with the projection of a greater radiation effect to that material having the highest upper shelf energy (9). That is, the radiation reduction in upper shelf may be less for material having a relatively low preirradiation upper shelf than material having a high preirradiation upper shelf, assuming that radiation sensitivities measured in terms of transition temperature elevation are equal. Overall, Fig. 12 points out a particular problem encountered in the experimental isolation of potential variables affecting the upper shelf.

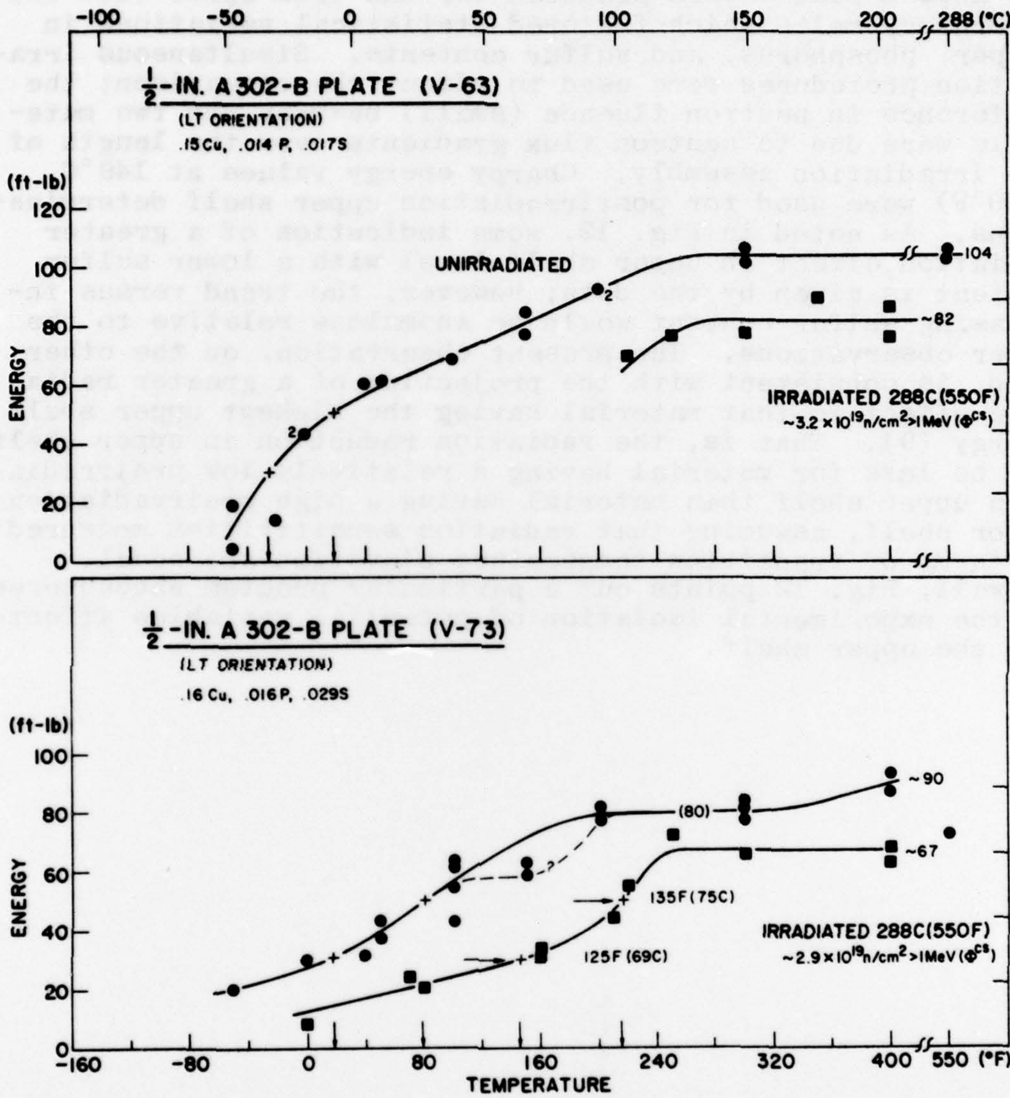

Fig. 12 — Postirradiation Charpy-V upper shelf degradation observed for two A302-B steel plates (laboratory melts) which differ in sulfur content

III. THERMAL SHOCK-RELATED INVESTIGATIONS

A. Investigation of Warm Prestress for the Case of Small ΔT During a LOCA

F. J. Loss, R. A. Gray, Jr., and J. R. Hawthorne

BACKGROUND

During a loss of coolant accident (LOCA) and operation of the emergency core cooling system, the inside wall of a nuclear pressure vessel is subjected to high thermal stresses (i.e., thermal shock) that may cause extension of a pre-existing flaw. During this event, the applied K_I can achieve a maximum early in the transient as illustrated in Fig. 13. However, the maximum K_I may not exceed the critical (K_{Ic}) level for crack initiation until a later time at which the loading has decreased from its peak. The fact that the material was loaded, at elevated temperature, to a value that exceeds K_{Ic} at some lower temperature is termed warm prestress (WPS). It is believed that this phenomenon can preclude crack extension when K_I equals K_{Ic} during a thermal shock accident.

The potential benefit of WPS during a LOCA is that this phenomenon can result in a predicted crack extension that is much less than the value computed from an elastic analysis that does not consider WPS. In order to establish a technical basis for the use of WPS, an experimental program was undertaken in which notched three-point bend specimens were mechanically loaded to simulate the load versus temperature path in the region of a longitudinal flaw during a LOCA as in Fig. 13 (10).

This study verified the hypothesis that failure does not occur during the period when K_I decreases with time following WPS even though the K_I level exceeds the K_{Ic} of the virgin material. Furthermore, it was demonstrated that WPS produces an effective elevation in K_{Ic} whose magnitude depends on (a) the level of WPS, (b) the magnitude of the ΔT between the temperature of WPS (T_{WPS}) and the failure temperature (T_F) (Fig. 13), and (c) the amount of unloading of the crack-tip region from the warm prestress level. These observations were used to project the degree of crack extension during a LOCA in a reference calculational model (RCM) (11) of a commercial, pressurized water reactor vessel. The RCM was used to construct a "worst-case" condition in terms of a steel that is highly sensitive to irradiation coupled with a high fluence level such as encountered near the end of vessel life.

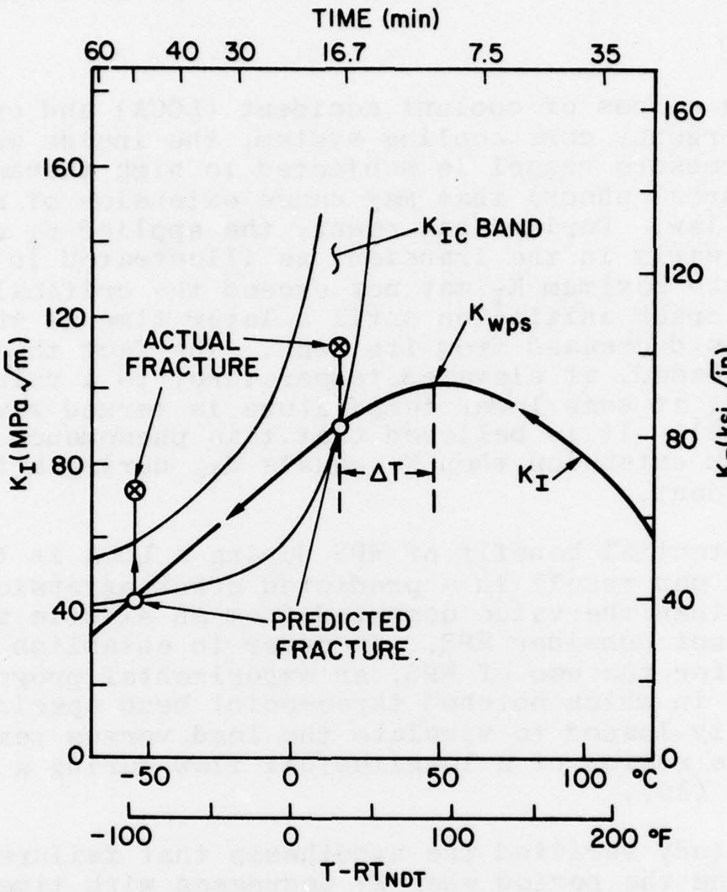

Fig. 13 — Representation of the K_I levels at the tip of a longitudinal flaw in a nuclear pressure vessel during a LOCA-ECCS. The time scale originates with the LOCA;RT_{NDT} is the reference temperature for the material defined in Section III, ASME Boiler and Pressure Vessel Code.

The preceding program investigated a wide range of parameters that, in some cases, imposed conditions that were more severe than those projected for the LOCA-ECCS. Also, because of limited material availability, it was not possible to address the case of a small ΔT. Since the latter is characteristic of the projected behavior during a LOCA, a follow-on study was undertaken to demonstrate the phenomenon of WPS in terms of a small ΔT and to develop a correspondence with the results of the preceding program.

EXPERIMENTAL APPROACH

From the calculations of the RCM under "worst-case" conditions (11), it can be concluded that ΔT can vary from a minimum of zero degree C at a relative crack depth of 0.2 to approximately 95°C at a relative depth of 0.5. In other words, there exists no "typical" ΔT. Of course, WPS is effected only for values of ΔT that are greater than zero. As part of the preceding study (10), the smallest value of ΔT imposed on the material was approximately 95°C, which corresponds to a very deep crack in the vessel. The goal of the present study was to impose a ΔT as small as practical to simulate the behavior of a crack whose initial depth lies between an a/W of 0.2 and 0.5.

As shown in Fig. 14, it is difficult to impose a very small ΔT. That is, the specimen first must be loaded at a temperature close to the lower bound of the K_{Ic} band (Path AB). If this boundary has not been accurately defined, premature failure may result upon loading to the desired level of WPS, K_{WPS}. The smallest ΔT that can be achieved experimentally is therefore established by the difference between: (a) the lowest temperature at which the specimen can be successfully loaded to K_{WPS}, and (b) the highest temperature at which K_I first intersects the K_{Ic} band (ΔT corresponding to Path BC). Unfortunately, if failure does not occur when the K_{Ic} level is reached under the preceding loading sequence, it is not possible to state whether this desirable outcome was due to the expected elevation of "effective" K_{Ic} by the WPS or if it was due to the fact that in the absence of WPS, this particular specimen would have failed near the upper bound of the K_{Ic} band. A statistically-designed experimental program was considered to resolve this uncertainty and identify the confidence one has in the WPS being the cause.

The test specimens were machined from a 210mm (8-1/4 in.) thick A533-B1 steel plate. The plate was specially purchased for this program to specifications currently used for nuclear pressure vessel construction. A description of the plate properties is given in Ref. 12. Three-point bend specimens of 76mm (3-in.) thickness were machined to ASTM E-399

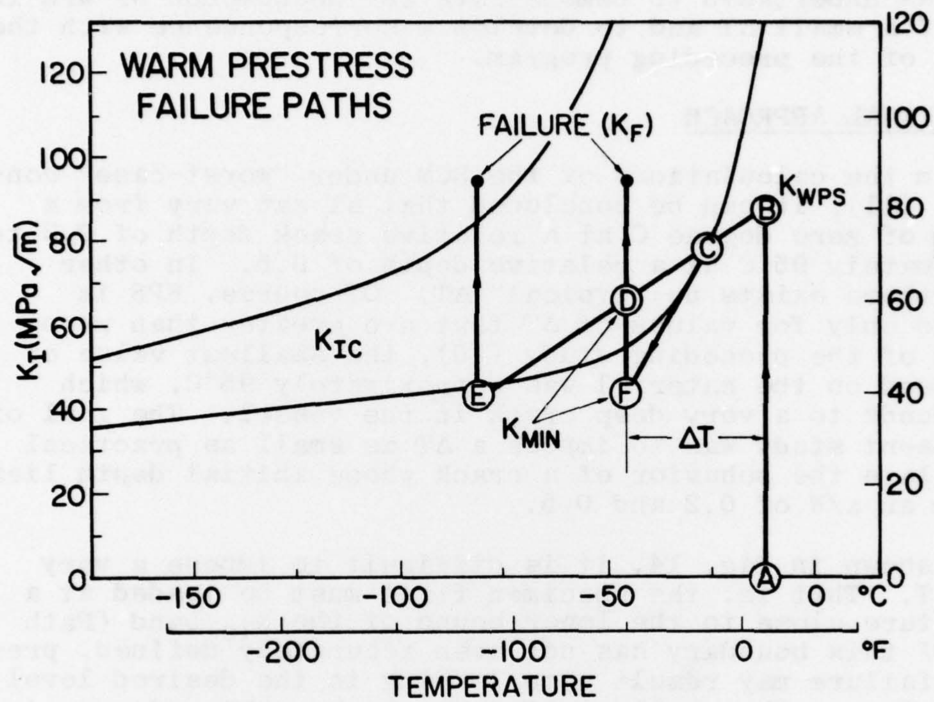

Fig. 14 — Failure paths for warm prestress specimens involving a small ΔT, which is representative of the crack tip behavior during a LOCA-ECCS

proportions with a span-to-width (S/W) ratio of 4.0. Each specimen was fatigue precracked at a maximum K_I level of 27 MPa$\sqrt{m}$ (25 ksi$\sqrt{in.}$) and for a distance of 6mm (1/4-in.) to provide an overall crack depth-to-width ratio (a/W) of 0.50.

The specimen loading sequence was designed to simulate a typical K_I vs temperature path of the crack-tip region as shown in Fig. 13. Warm prestressing was accomplished by slowly loading each specimen at a fixed temperature to the desired level of K_{WPS}. At this point both the load and temperature were simultaneously decreased along the paths illustrated schematically in Fig. 14. Then, at a predetermined temperature, corresponding to K_{min}, the specimen was isothermally loaded to failure. It should be noted that the absolute temperatures used in this program were much lower than those which would occur during a LOCA. With a LOCA it is assumed that the K_I vs temperature trend has been markedly elevated as a result of the neutron bombardment during service. Since the present program utilized unirradiated material, an effective increase in K_{Ic} due to WPS could be demonstrated only at low temperatures where the material behaves in a linear-elastic manner.

K_{Ic} TRENDS

It is essential to characterize the K_{Ic} trends of the program material in order to permit assessment of the effective elevation in K_{Ic} attributable to WPS. The K_{Ic} behavior as a function of temperature was determined with 76mm thick specimens that were identical to those used for the WPS tests. The results are illustrated in Fig. 15; a listing of the data appears in Ref. 12. While the K_{Ic} scatterband may seem large, it is essentially identical to that exhibited by the A533-B1 plate (HSST-02) used in the preceding investigation (10) when account is taken of the additional K_{Ic} data developed by NRL in that study.

A few of the data points shown in Fig. 15 violate the E-399 thickness requirement. The K_{Ic} values for these specimens were therefore computed from the J-integral value at the point of maximum load, i.e., K_{Jc}, from the relationship

$$K_{Jc}^2 = E\, J_{Ic} \qquad (2)$$

where E is the elastic modulus. Since the fractures propagated in a cleavage (brittle) mode starting from the fatigue precrack, the J value computed on the basis of maximum or failure load, represents the initiation value, J_{Ic}. In other words, there existed no stable crack extension with rising load that is often associated with elastic-plastic fractures.

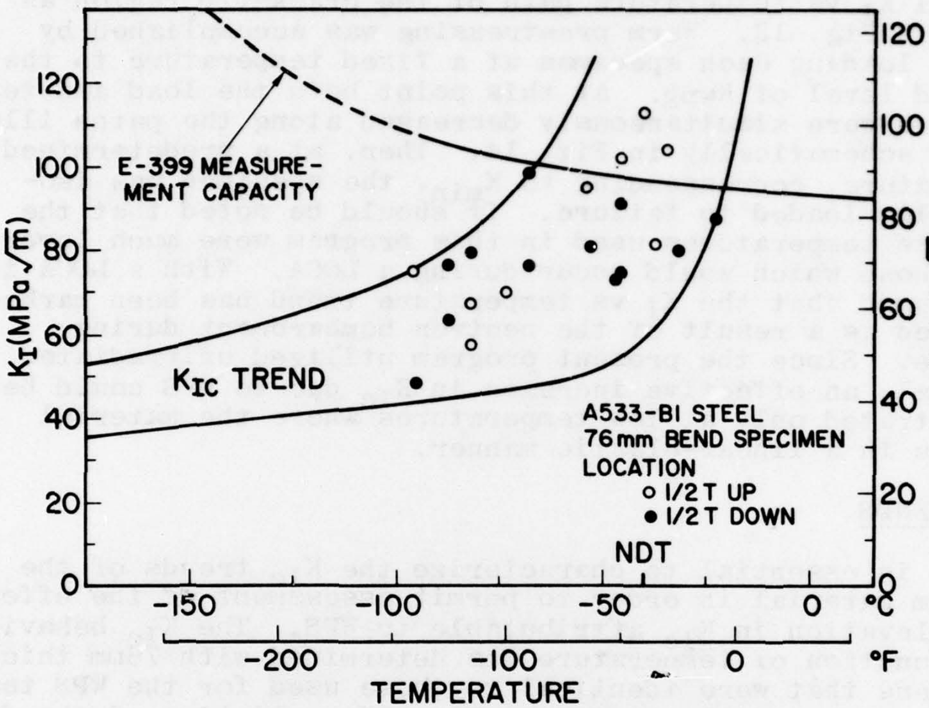

Fig. 15 — K_{Ic} trends for the program material. The shapes of the upper and lower boundaries of the scatterband are based on K_{Ic} data for a different heat of A533-B1 steel (10) that encompass a larger temperature range from that investigated in the present study.

WARM PRESTRESS RESULTS

Results of the WPS experiments are presented in Fig. 16; a listing of the data appears in Ref. 12. The majority of the specimens were loaded to a K_{WPS} of 88 MPa$\sqrt{m}$ (80 ksi$\sqrt{in.}$). This K_{WPS} level is the highest that would be permitted in terms of K_{Ic} measurement capacity defined by E-399 for a specimen of 76mm thickness. The failure paths followed those illustrated schematically in Fig. 14. The specimens were approximately equally divided between a 25 percent and a 50 percent unloading from the K_{WPS} level. Various ΔT increments were employed ranging from 22 to 50°C (40 to 90°F) but the majority of tests were conducted with a ΔT of 33°C (60°F). Three specimens were subjected to a K_{WPS} "overload" to a level of 124 MPa$\sqrt{m}$ (113 ksi$\sqrt{in.}$). This is the K_I level which would have been permitted by E-399 for a 150mm (6 in.) thick specimen.

Two observations from the results shown in Fig. 16 summarize the essence of this investigation.

- No specimens failed during the simultaneous unloading and cooling even though the critical K_{Ic} for the virgin material was attained.
- Without exception, the failure levels exceeded the level of warm prestress.

With respect to the first observation, it was expected from physical reasoning that failure would not take place during unloading and cooling even though the K_{Ic} level was reached. This behavior is consistent with that observed during the previous investigation (10) and is believed to result from the fact that the decreasing level of strain at the crack tip during unloading removes a necessary condition for fracture. The second observation, that of a failure level greater than K_{WPS}, is also consistent with a projection of the trends evolved in the preceding study.

With respect to the failures illustrated in Fig. 16, it is observed that all but two lie within the K_{Ic} scatterband. Thus, a statistical analysis is required in order to more confidently conclude whether the failure levels above K_{WPS} were: (a) the result of an effective elevation in K_{Ic} due to WPS, or (b) the result of K_I fractures that normally would have exceeded the K_{WPS} in the absence of WPS. For example, all but one of the ten failures at -46°C lie close to one another. The one datum which exhibits a K_F near the upper K_{Ic} boundary (and possibly others) is therefore believed to have resulted from an inherently high toughness so that its failure level does not reflect the influence of

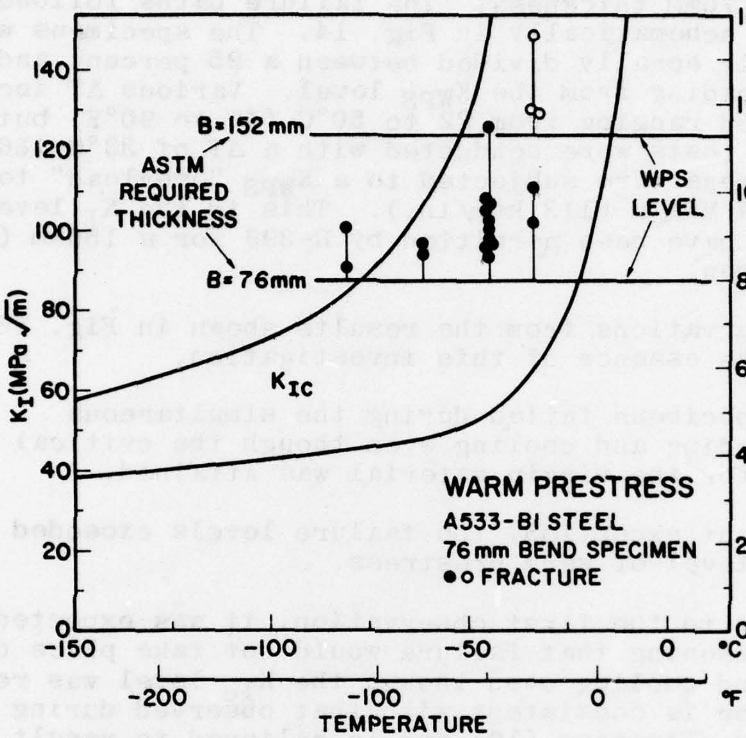

Fig. 16 — Results of WPS experiments involving a small ΔT. Note that all failures are above the level of WPS that was imposed at a higher temperature

WPS. However, the lack of scatter otherwise exhibited by the data at -46°C is considered significant since this is not typical of the large scatter observed with the K_{Ic} tests of virgin material (Fig. 15).

In order to clarify the uncertainty in the data described above, statistical analyses of the data have been performed (12). It was assumed that the median of the K_{Ic} data (Fig. 15) passes through 88 MPa$\sqrt{m}$ at -46°C. It is observed that this temperature is the same as the failure temperature for ten specimens illustrated in Fig. 16. Under the above assumption, it is concluded that, in the absence of WPS (the null hypothesis), there is a better than 99 percent probability that at least one of the ten failures at -46°C should have been less than 88 MPa$\sqrt{m}$. (In statistical terminology the observed significance level is less than 1 percent.) Since all of the failures at this temperature were higher than 88 MPa$\sqrt{m}$, it is concluded that this result must be due to the effects of WPS (the absence of WPS is rejected).

In addition, it was observed that the results of Fig. 16 exhibit no definite trend as a function of the ΔT value. This is contrary to the observation made in the preceding study (10) wherein the effective elevation in K_{Ic}, due to WPS, diminished with increasing ΔT. With the present investigation, the variation in ΔT is only 28°C (50°F) compared with a ΔT range of 220°C (400°F) in the previous study. It is concluded that the range of ΔT associated with the present tests is too small to distinguish variations due to this variable in the effective K_{Ic}. Finally, no trend could be attributed to the degree of unloading from the K_{WPS} level (i.e., 25 percent vs 50 percent unloading). This result is also consistent with the previous study. In that investigation, a trend in the fracture levels was observed only between a partial unloading of 30 and 60 percent with decreasing temperature and a complete unloading at the WPS temperature.

CONCLUSIONS

The results of this study are consistent with the trends evolved previously (10) and therefore permit an optimistic assessment concerning vessel integrity during a LOCA. The major observations concerning the specimen behavior are: (a) failure did not occur during the simultaneous unloading and cooling following WPS even though the critical K_{Ic} of the virgin material was attained, and (b) without exception, the failure level exceeded the level of WPS.

A statistical analysis of the specimen fractures within the K_{Ic} scatterband has demonstrated that WPS produces an

increased resistance to crack initiation. For the case of a small ΔT it is concluded that while WPS may not elevate the toughness of a material whose K_{Ic} would be greater than K_{WPS}, it will produce an effective K_{Ic} elevation in material of lower toughness so that a value less than K_{WPS} will not be observed.

The previous study suggested that the effective increase in K_{Ic} due to WPS would improve with decreasing ΔT. The present study with a small ΔT suggests that this effect has saturated and that a further elevation in K_{Ic} will not occur. The authors have suggested that the effective elevation in K_{Ic} is related to the change in yield strength that occurs over the ΔT increment. Thus, the change in yield strength rather than ΔT may be a more significant parameter to characterize the benefit of WPS.

With respect to crack extension during a LOCA it was concluded that this event is precluded during the period of decreasing stress intensity with time following the WPS since this behavior removes a necessary condition for fracture initiation. However, minor temperature fluctuations in the ECCS water also will occur. This variation could result in a momentary reversal in the monotonic decrease in K_I at the crack tip. Fortunately, the present studies have demonstrated that minor perturbations in an overall decreasing K_I trend are not significant in that fracture is prevented unless the WPS level is exceeded.

Collectively, the two studies have provided a means for projecting vessel integrity during a LOCA-ECCS based upon the WPS phenomenon. While certain areas may require additional study to fully characterize vessel performance for all material conditions, it is concluded that WPS can provide a positive mechanism to limit crack extension during a thermal shock. In terms of a reference calculational model of the vessel, under assumed worst case conditions, it was concluded earlier that while WPS cannot prevent the initiation of shallow flaws, this phenomenon will limit crack penetration to a depth of one-third of the vessel wall. Thus, WPS may form a key element upon which to base assurance of vessel integrity during a LOCA.

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